that the same universal law of gravitation should apply to a falling apple and to the planets in orbit about the sun, at 10^{12} times the distance.

Problems

1.1 An electron of energy 20 GeV is deflected through an angle of 5° in an elastic collision with a stationary proton. What is the value of the square of the 4-momentum transfer, q^2, and down to what approximate distance does such a collision probe the internal structure of the proton? (The mass of the electron can be neglected compared with the energies involved. The proton mass Mc^2 is 0.938 GeV.)

1.2 The flux of primary cosmic rays averaged over the Earth's surface is approximately 1 cm^{-2} s^{-1}, and their average kinetic energy is 3 GeV. Show that the power transferred to the Earth from cosmic rays is about 2.5 gigawatt. (Earth radius = 6400 km.)

1.3 The values of mc^2 for the pion π^+ and muon μ^+ are 139.57 MeV and 105.66 MeV respectively. Find the kinetic energy of the muon in the decay $\pi^+ \to \mu^+ + \nu_\mu$ assuming that the neutrino is massless. For a neutrino of finite but very small mass m_ν show that, compared with the case of a massless neutrino, the muon momentum would be reduced by the fraction

$$\frac{\Delta p}{p} = -\frac{m_\nu^2(m_\pi^2 + m_\mu^2)}{(m_\pi^2 - m_\mu^2)^2} \simeq -\frac{4m_\nu^2}{10^4}$$

where m_ν is in MeV.

1.4 Deduce an expression for the energy of a γ-ray from the decay of the neutral pion, $\pi^0 \to 2\gamma$, in terms of the mass m, energy E and velocity βc of the pion and the angle of emission θ in the pion rest frame. Show that if the pion has spin zero, so that the angular distribution is isotropic, the laboratory energy spectrum of the γ-rays will be flat, extending from $E(1 + \beta)/2$ to $E(1 - \beta)/2$. Find an expression for the disparity D (the ratio of energies) of the γ-rays and show that $D > 3$ in half the decays and $D > 7$ in one quarter of them.

1.5 (a) A negative muon, when brought to rest in liquid hydrogen, can form a molecular ion H_2^+ by displacing an electron. Why? (b) Hydrogen contains a small amount of the heavier isotope deuterium, and it is found that negative muons stopping in hydrogen eventually form molecular ions HD^+. Why? (c) What is the typical internuclear distance in such an ion? (d) If the two nuclei fuse to form ^{3}He, what may happen to the muon?

1.6 The ρ meson is a particle of spin $J = 1$ and mass 770 MeV/c^2 occurring in three charge states ρ^+, ρ^0, ρ^-. It decays to a pair of spinless pions. Show that while $\rho^\pm \to \pi^0\pi^\pm$ and $\rho^0 \to \pi^+\pi^-$ are allowed, $\rho^0 \to \pi^0\pi^0$ is forbidden.

1.7 State which of the following reactions are allowed by the conservation laws and which

Answers to problems

Chapter 1

1.1 $q^2 = 2.81$ GeV^2; 0.74 fm.

1.4 $E_\gamma = E_\pi(1 + \beta \cos\theta)/2$; $dN/dD = 2/(D+1)^2$.

1.5

(a) Binding energy of $(H_2\mu)^+$ larger than $(H_2e)^+$.

(b) Reduced mass $\mu_H = m_\mu/(1 + m_\mu/M_H) < \mu_D = m_\mu/(1 + m_\mu/M_D)$.

(c) 3×10^{-11} cm.

(d) HD $\to$ ^{3}He $+ \mu + 5.4$ MeV.

(For references, see G. Feinberg and L. Lederman, *Ann. Rev. Nucl. Sci.* **13**, 431, 1963.)

1.7 Reactions 1,2,5 allowed. Reaction 3 forbidden by lepton conservation. Reaction 4 forbidden by conservation of strangeness in strong interactions.

1.8 6.7×10^{10} cm^{-2} s^{-1}.

1.9 (b) 26.5 *cm*, $(c)10^{-7}$.

1.10

(a) $\theta_{max} = 0.80$ rad, $p = 7.96$ GeV/c.

(b) $\theta = 0$, $p = 9.21$ GeV/c, $q^2_{max} = 15.6$ GeV^2.

Chapter 2

2.1 $\simeq 10^6$.

2.2 $|\Delta e/e| > \sqrt{(G_N M^2/e^2)} = 10^{-18}$.

2.4 17.6 mb.